Examination of the Role of Physical Resolution and Scale on Sediment and Nutrient Yields

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Abstract

Currently, watershed delineation and extraction of stream networks are accomplished with GIS databases of digital elevation maps (DEMs). The most common method for extracting channel networks requires the *a-priori* specification of a critical source area that is required for channel initiation. There are no established guidelines on how to select the critical source area. The critical source area could be selected by identifying an optimal scale of geomorphologic resolution such that further refinement in spatial scale does not contribute to a significant improvement in predicting design quantities at the watershed outlet. In this study, the Soil and Water Assessment Tool (SWAT) model integrated into the BASINS framework was utilized for this purpose. The BASINS framework allows the user to automatically or manually delineate the watershed based on a DEM. The SWAT model was calibrated and validated at Dreisbach and Smith Fry, two subwatersheds of the Black Creek watershed in the Maumee River basin in northeast Indiana. After calibration, several stream definition values were used to estimate total sediment yield for the Smith Fry (Site 2) subwatershed. This study showed that there was no clear critical source area that could be identified for stream definition in SWAT modeling. However, an optimal stream definition value was suggested from a plot of sediment yield versus number of subbasins.

Introduction

Currently, watershed delineation and extraction of stream networks are accomplished with GIS databases of digital elevation maps (DEMs). The most common method for extracting channel networks requires the *a-priori* specification of a critical source area that is required for channel initiation. The nature of the channel network is very sensitive to this critical source area, with drainage density decreasing exponentially with increasing critical source area. Thus, the channel network could be viewed at multiple scales within the same watershed. There are no established guidelines on how to select the critical source area. Thus, for the same watershed and DEM, users may obtain markedly different channel networks, and subsequently the watershed model results based on the channel network could be affected as well. One needs to identify an optimal scale of geomorphologic resolution such that further refinement in spatial scale does not contribute to a significant improvement in predicting design quantities at the watershed outlet.

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There are various models for predicting the design quantities such as stream flow, sediment yield, and nutrient load. The Soil and Water Assessment Tool (SWAT) model has been widely used for this purpose. SWAT is a physically based simulation model, operating on a daily time step. SWAT partitions the watershed into sub-watersheds, each of which is treated as an individual unit. The model also has been integrated into USEPA's modeling framework, Better Assessment Science Integrating Point and Nonpoint Sources (BASINS). This framework provides the user with a watershed delineation tool that allows the user to automatically or manually delineate the watershed based on a DEM. A stream definition value is required by the delineation tool for watershed delineation. Selecting several different values for stream definition and comparing the predicted sediment and nutrient yields, the role of sub-watershed division on predicted responses of water and contaminant fluxes from the watershed were examined to address the issue of spatial resolution required for modeling purposes. Nonetheless, the SWAT model needs to be calibrated and validated for the study area to ensure that model parameters are representative for the study area.

SWAT model description

SWAT is a physically based simulation model, operating on a daily time step (Neitsch et al., 2002a,b). The model was originally developed to quantify the impact of land management practices in large, complex watersheds with varying soils, landuse, and management conditions over a long period of time. SWAT uses readily available inputs and has the capability of routing runoff and chemicals through streams and reservoirs, and allows for addition of flows and inclusion of measured data from point sources. It is capable of simulating over long periods for studying the effect of management changes. Moreover, SWAT has the ability to evaluate the impacts of different management scenarios on water quality, sediment, and agricultural chemical yield in large, ungaged basins. Major components of the model include weather, surface runoff, return flow, percolation, ET, transmission losses, pond and reservoir storage, crop growth and irrigation, groundwater flow, reach routing, nutrient and pesticide loading, and water transfer. For simulation, SWAT partitions the watershed into subunits including subbasins, reach/main channel segments, impoundments on main channel network, and point sources to set up a watershed. Subbasins are divided into hydrologic response units (HRUs) which are portions of subbasins with unique landuse/management/soil attributes.

The Study Area

A study on the Black Creek watershed in northeast Indiana was conducted in the 1970s and early 1980s to examine the short term effects of soil and water conservation techniques on improving water quality by reducing sediment and nutrient loads leaving the watershed. This watershed, located in Allen County, Indiana, is a 5,000 (ha) watershed in the Maumee River basin. In this previous study, detailed water quality monitoring was carried out during the duration of the project. Nineteen major monitoring stations were established within the watershed. However, data collected from automated samplers located at Site 2 (Smith Fry) and Site 6 (Dreisbach) were the most complete and were used for most of the analysis reported in the project. The areas of the Smith Fry and Dreisbach watersheds (shown in Fig. 1) are 942 ha and 714 ha, respectively. Daily precipitation, stream flow, and sediment and nutrient loads were recorded at the outlet of these two subwatersheds. Landuse in the Dreisbach watershed is mostly pasture in the upper portion while cropland is wide spread in the remainder of the watershed. Landuse in the Smith Fry subwatershed is mostly croplands. There were 26 management practices installed in the Dreisbach subwatershed in 1974 while this number was 6 for Smith Fry subwatershed. The BMPs were installed in the Smith Fry subwatershed in 1975.

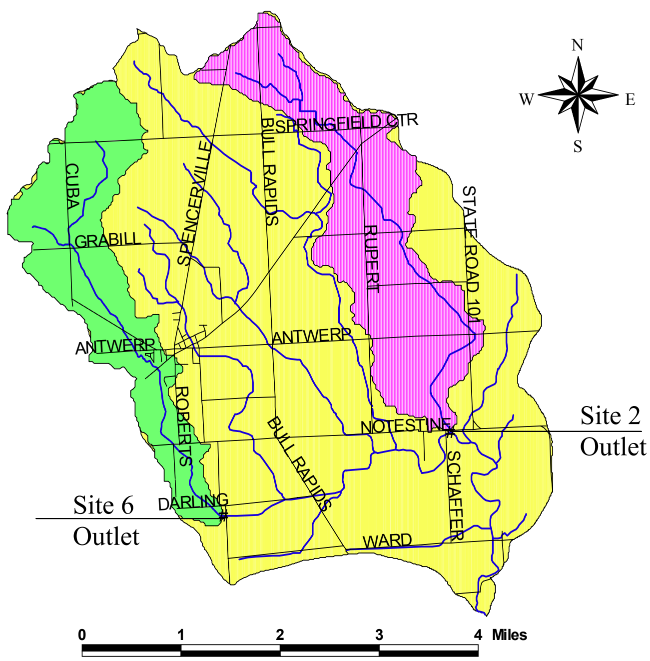


Figure 1. Black Creek Watershed

Model Inputs

The SWAT model requires inputs on weather, topography, soil, landuse, management, stream network, ponds, and reservoirs. The BASINS framework was used to develop the input parameters.

Climate Inputs: Daily precipitation from January 1974 to June 1977 was obtained from the monitoring stations located at the outlets of the Dreisbach and Smith Fry sub-watersheds. The elevation of the outlet of Dreisbach sub-watershed is 755 (ft) while the elevation of the outlet of Smith Fry sub-watershed is 722 (ft). Daily precipitation was obtained from the Fort Wayne station (Station ID: 123037) monitored by Purdue University Applied Meteorology Group for 1902 to 1973 and 1978 to 2002. This station is located at 41°06'N / 85°07'W (LAT/LONG) which is 20 miles southwest of the outlet of the Black Creek watershed. The elevation of the Fort Wayne airport station is 740 (ft). Daily maximum and minimum temperatures were obtained from the Fort Wayne station.

Elevation Map: A 30-m resolution, UTM NAD83 projected Digital Elevation Map (DEM) was obtained from the National Elevation Dataset dated 2001.
Soils: Soil data were obtained from the Soil Survey Geographic Database. Detailed digital representation of County Soil Survey maps was published by the Natural Resources Conservation Service (USDA-NRCS).
Landuse: Landuse map was digitized into ArcView shapefile format from Black Creek project historical files. The landuse maps for 1975, 1976, 1977, and 1978 were extracted from aerial photos dated 1975, 1976, 1977, and 1978, respectively.
Flow, Sediment, and Nutrient Data: Daily stream flow discharge, sediment, and nutrient yields were measured at the two monitoring stations at the outlets of the Dreisbach and Smith Fry sub-watersheds from 1973 to 1978.

Base Flow Separation

An automated hydrograph separation model "ISEP" was used to determine the relative contribution of surface runoff and ground water to total stream flow. This model was developed in the Department of Agricultural and Biological Engineering, Purdue University. The separated hydrographs were verified by another flow separation model (Arnold et al., 1999). The results of the two models were consistent in their determination of contributions of the surface runoff and base flow parts of the total stream flow.

Evaluation of Model Performance

The coefficient of determination R^2 and the coefficient of efficiency $E_{N\text{-}S}$ (Nash and Sutcliff, 1970) along with mean and standard deviation were used to evaluate model predictions. The coefficient of determination is the square of the Pearson's product-moment correlation coefficient. This coefficient describes the proportion of the total variances in the observed data that can be explained by the model.

$$R^2 = \frac{\left[\sum_{i=1}^{N}(O_i-\overline{O})(P_i-\overline{P})\right]^2}{\left[\sum_{i=1}^{N}(O_i-\overline{O})^2\right]\left[\sum_{i=1}^{N}(P_i-\overline{P})^2\right]}\text{; where}$$

O_i : observed stream flow
$\overline{O}$: average of observed stream flow
P_i : predicted stream flow
$\overline{P}$: average of predicted stream flow

R^2 ranges from 0 to 1. An R^2 value equal to one is indicative of a perfect model prediction. The coefficient of efficiency is defined as:

$$E_{N-S} = 1.0 - \frac{\left[\sum_{i=1}^{N}(P_i-\overline{P})^{2}\right]}{\left[\sum_{i=1}^{N}(O_i-\overline{O})^2\right]}$$

$E_{N\text{-}S}$ ranges from to 1 to $-\infty$, with values closer to 1 indicating a better prediction. If $E_{N\text{-}S}$ is negative or very close to zero the model prediction is considered "unacceptable or poor". The coefficient of efficiency is indicative of how well the plot of observed versus predicted values fit the 1:1 line.

Model Calibration

The SWAT model is sensitive to many input parameters related to the soil, landuse, management, weather, channels, aquifer, and reservoirs. An initial sensitivity analysis of SWAT revealed that stream flow is most sensitive to curve number. In this study, a further sensitivity analysis was performed that showed the model is highly sensitive to parameters called CN, SOL_AWC, ESCO, GWQMN, and GW_REVAP for stream flow calibration, USLE-P, and USLE-C for sediment calibration, and SOL-SOLP, and SOL-ORGP for phosphorous calibration.

A traditional model calibration approach is to partition the measured stream flow time series into calibration and validation periods. The characteristics of a good calibration data set have been subject of much discussion (James and Burges, 1982; Gupta and Sorooshian, 1985; Beck, 1987; and Sorooshian and Gupta, 1995). However, there are only general, qualitative guidelines for the selection of the calibration data set. Obviously, a good calibration data set contains sufficient information to fulfill the goals of the study. Sorooshian et al. (1983) showed that a single year of measured stream flow data could be adequate to calibrate a hydrologic model if it contains the right information. Typically three to five years of data are required in calibration of a hydrologic model. For stream flow calibration, the measured daily stream flow series from January 1975 to December 1978 was split into two sets. The first set of flows from January 1975 to June 1977 (30 months) was utilized for calibration. The rest of the time series containing 18 months of measured stream flow was used for validation of the model. Both calibration and validation procedures were performed on a monthly basis. Sediment and nutrient calibration period included monthly data from Jan. 1974 to Dec. 1975. The observed monthly sediment and nutrient yields from Jan. 1975 to May 1977 were used for sediment and nutrient validation. The procedure for model calibration is shown in Figure 2 (adopted from Santhi et al., 2001). The result of the calibration procedure is summarized in Table 1.

Table 1. Results of Calibration Procedure

Variable	Dreisbach (Site 6)				Smith Fry (Site 2)			
	Mean		R^2	E_{N-S}	Mean		R^2	E_{N-S}
	Obs	Sim			Obs	Sim		
Stream Flow (mm)	16.01	15.15	0.90	0.80	18.53	19.64	0.87	0.69
Surface Runoff (mm)	14.57	14.08	0.88	0.75	15.49	17.49	0.85	0.65
Sediment (t/ha)	0.027	0.027	0.86	0.59	0.12	0.11	0.96	0.89
Min P (kg/ha)	0.020	0.016	0.86	0.67	0.012	0.011	0.9	0.78
Total P (kg/ha)	0.077	0.079	0.87	0.75	0.08	0.068	0.64	0.38

Model Validation

The calibrated model was tested on a set of measured data that was not used in the calibration procedure. The goal of model validation is to verify whether the model prediction is satisfactory on different data sets. In addition, the validation data set should represent the condition for which the model results are of interest. Flow data were validated from July 1977 to December 1978, and sediment and nutrient yields were validated from January 1975 to May 1977. The result of the validation procedure is summarized in Table 2.

Table 2. Results of the Validation Procedure

Variable	Dreisbach (Site 6)				Smith Fry (Site 2)			
	Mean		R^2	E_{N-S}	Mean		R^2	E_{N-S}
	Obs	Sim			Obs	Sim		
Stream Flow (mm)	17.46	19.56	0.87	0.73	18.03	21.16	0.88	0.74
Surface Runoff (mm)	15.66	18.50	0.88	0.75	15.15	19.05	0.87	0.74
Sediment (t/ha)	0.032	0.035	0.84	0.70	0.049	0.058	0.66	0.43
Min P (kg/ha)	0.012	0.012	0.9	0.79	0.014	0.011	0.54	0.19
Total P (kg/ha)	0.063	0.066	0.68	0.43	0.071	0.081	0.38	0.01

Figure 3 shows the results of calibration and validation of SWAT model at Site 6.

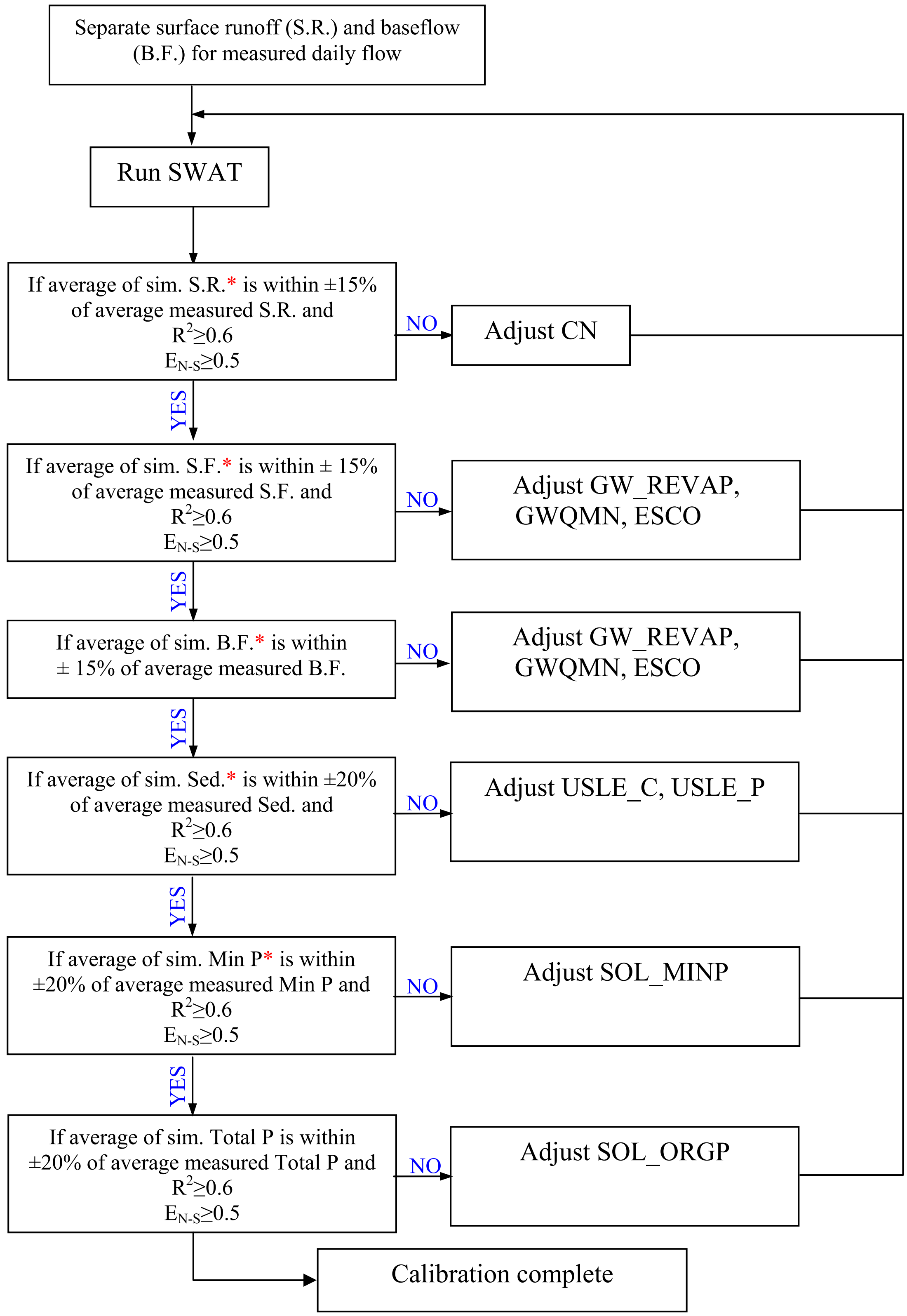
Resolution Effects on Sediment Yield

The SWAT model integrated into the BASINS framework was calibrated and validated for the Dreisbach and Smith Fry subwatersheds. Only results for the Dreisbach watershed are shown in Fig. 3 for brevity. The set of model parameters including CN, GWQMN, USLE-P, and USLE-C calibrated for the Dreisbach subwatershed was consistent with the ones for the Smith Fry subwatershed. However, the stream definition value for Dreisbach was 5 (ha) while this value was 8 (ha) for Smith Fry. Stream definition along with the DEM plays a significant role in determining the size and number of subwatersheds created by automated watershed delineation tool built in the BASINS framework. The SWAT model provides users with a minimum, maximum, and suggested value as critical source area that is required for channel initiation. Although, there are no established guidelines on how to select the critical source area. To examine the role of critical source area in sediment and nutrient yield, seven stream definition values (within the range suggested by the SWAT model) were used to estimate total sediment yield over Smith Fry watershed (Site 2). The model parameters were the same as the calibrated and validated ones. The stream definition values, number of subbasins, and total Sediment yield for the period from 1970 to 2000 are summarized in Table 3.

Table 3. Stream Definition Values, Number of Subbasins, Stream Flow, Surface Runoff, and Sediment Yield, for the Period from 1970 to 2000, Smith Fry (Site 2)

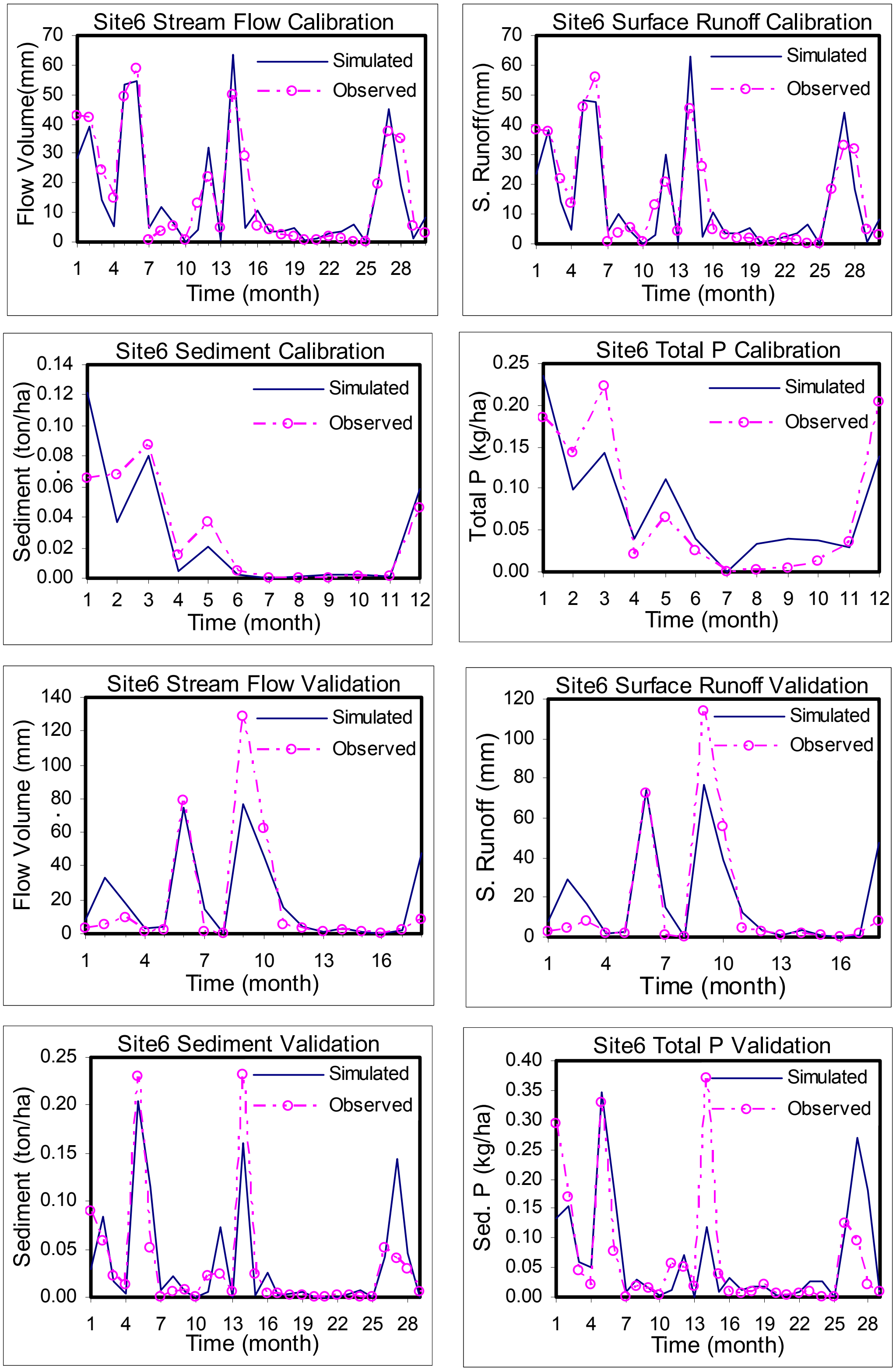
Stream Definition (ha)	5	10	15	30	50	120	290
Number of Subbasins	63	33	19	11	7	3	1
Average Stream Flow (mm)	322.2	322.6	310.6	318.2	324.3	327.1	324.4
Average Surface Runoff (mm)	269.9	271.1	266.7	275.2	280.7	287.8	288.3
Sediment Yield (ton/ha)	38.42	41.19	44.29	54.54	58.88	73.27	76.71

Figure 4 shows the annual sediment yield from the Smith Fry subwatershed for the period from 1970 to 2000.



* S.R.: surface runoff, S.F.: stream flow, and B.F.: base flow, Sed: sediment, Min P: mineral P

Figure 2. Calibration flowchart (adapted from Santhi et al., 2001)



*SDV: stream definition value

Figure 3. Calibration and Validation results at Site 6 (Dreisbach watershed).

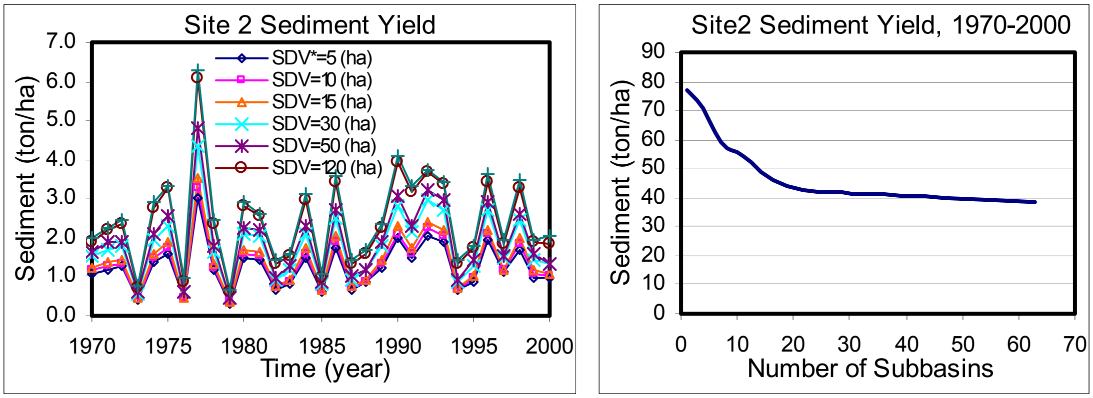


Figure 4. (a) Annual Sediment Yield at Site 2 for different resolutions. (b) Total Sediment Yield from 1970 to 2000 as a function of number of subbasins.

The results of the study (see Fig. 5a) indicated that there was no clear critical source area that could be determined from the SWAT model, perhaps because SWAT lumps portions of the watershed with unique landuse/management/soil attributes into hydrologic response units (HRUs) for simulation. SWAT uses a modification of the SCS curve number method or Green & Ampt infiltration method to compute surface runoff volume for each HRU. The SCS curve number method was used in this study. Once the DEM, soil series and landuse attributes of the watershed are defined, the stream flow and surface runoff volumes are estimated by the model independent of the stream definition value. Therefore, simulated stream flow and surface runoff hardly change for different stream definition values. This is consistent with the results of this study presented in Table 3. The small differences in the results were due to HRU distribution used for modeling the watershed. However, SWAT estimates erosion and sediment yield for each HRU with the Modified Universal Soil Loss Equation:

$$sed = 11.8(Q_{surf} \cdot q_{peak} \cdot area_{hru})^{0.56} \cdot K_{USLE} \cdot C_{USLE} \cdot P_{USLE} \cdot LS_{USLE} \cdot CFRG$$

Using the same soil series, landuse, and management scenarios, none of the parameters in this equation are influenced by changing the channel initiation parameter except for LS_{USLE}, the USLE topographic factor. This parameter is averaged for each HRU within a subbasin. Selecting a different stream definition value changed the stream network and the number and size of delineated subbasins in the watershed. Consequently, LS_{USLE} corresponding to each HRU was different for different stream definition values. The simulated sediment yield was greatly influenced by the minimum value for stream network initiation as presented in Table 3. Plotting sediment yield versus the number of subbasins delineated by the model (Fig. 5b) could be useful for selection of a value for stream definition. The suggested value for Smith Fry subwatershed was 10 (ha). The number of subbasins corresponding to this value was 33.

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